nature physics

SUPPLEMENTARY INFORMATION

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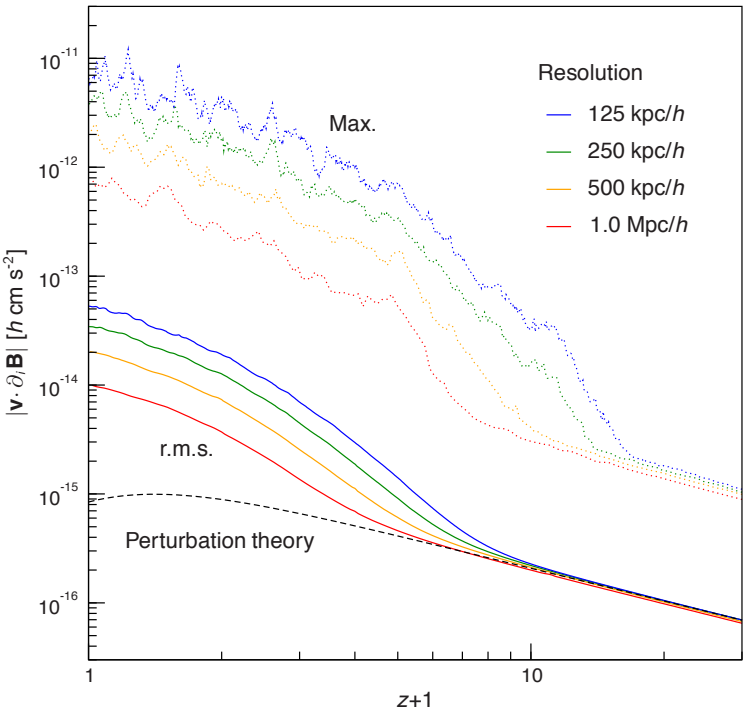
General relativity and cosmic structure formation



Supplementary Figure 1 | **Frame dragging.** Frame-dragging acceleration as a function of redshift z as measured in simulations of different spatial resolution. The solid lines correspond to mass-weighted r.m.s. values, whereas the dotted lines indicate the maximum value measured in the simulation volume, which was fixed to $(512\ \mathrm{Mpc}/h)^3$. The dashed black line shows the time evolution of the r.m.s. value as expected from perturbation theory. At high redshift, where perturbations are small and this calculation is therefore valid, the numerical curves converge on the expected behaviour. Small scales become nonlinear first, explaining why the departure from the theoretical curve depends on the resolution. We have checked that the effect of finite volume and realization scatter are less relevant.

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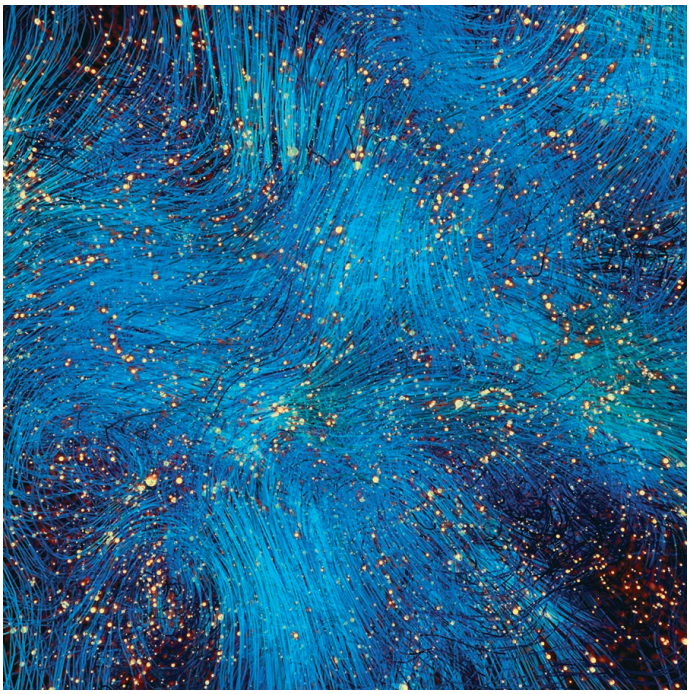

Supplementary Figure 2 | **Spin-1 perturbation (zoomed).** More detailed visualization of the spin-1 metric perturbation. Bright blobs represent halos of cold dark matter. A correlation between the configuration of the spin-1 field and the distribution of matter is clearly evident. Note also the large correlation length of the spin-1 field, indicating that the large scales dominate the amplitude.

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Supplementary Information file: spin1.mpg | **Cosmic evolution of spin-1 metric perturbation.** The video clip shows a relativistic simulation of cosmic structure formation. Dark matter halos are rendered as orange blobs scaled to their virial radius. The blue stream lines show the spin-1 component of the metric, **B**, which is responsible for frame dragging. Dense lines and lighter colour indicate large amplitude. The amplitude evolves over time and is largest at redshift $z\sim1$, just before dark energy starts to dominate the Universe.

Supplementary Information file: spin2.mpg | **Spin-2 metric perturbation at redshift zero.** The video clip shows the three-dimensional configuration of the spin-2 component of the metric at redshift $z=0$ for a relativistic simulation. Dark matter halos are rendered as orange blobs scaled to their virial radius. To visualize the spin-2 field, it is applied as affine transformation on a regular lattice of identical spheres. The shapes and sizes of the resulting ellipsoids indicate, respectively, the polarization and amplitude of the spin-2 field at that position. The lattice is "rolled in" and "rolled out" in order to also show the inner part of the volume.

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